CAN LINEAR LIGHT SOURCES BE BENEFICIAL TO PILOTS?

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INTRODUCTION

Presently, lighted delineation for runway and taxiway airfield systems uses discrete light sources in the form of raised and in-pavement light fixtures varying in color to indicate edges and centerlines of runways and taxiways. There have been suggestions both anecdotally and in published literature, that delineation practices using more continuous visual elements might provide superior visual cues to pilots navigating on the airfield than the primarily discrete visual elements used in the form of edge and centerline light fixtures. To assist the Federal Aviation Administration (FAA) in assessing the potential benefits of more continuous or linear visual delineation of runways and taxiways, a series of laboratory and field experiments was conducted by the Lighting Research Center (LRC). The primary objective was to investigate the influence of the length and spacing of delineation elements on visual acquisition under simulated airfield viewing conditions, including both static and dynamic situations.

BACKGROUND

As described above, published research as well as observations by operational staff at airports suggests that more continuous delineation of airfield taxiways and runways might provide superior visual guidance over conventional lighting practices. This section briefly describes existing lighting practices and summarizes published research on delineation, from both an aviation context and a roadway context. Table 1 summarizes several typical practices for runway and taxiway edge and centerline lighting [1]. The use of light fixtures to delineate the airfield can produce a sensation of a "maze of blue" where taxiways intersect with runways [2].

Table 1.
Representative Edge and Centerline Practices for Airfield Lighting.

Application	**Condition**	**Minimum Spacing (ft)[a]**
Runway Edge Lighting	General	200 ft
Runway Centerline Lighting	General	50 ft
Taxiway Edge Lighting	Short Section	50 ft
	Intermediate Section	100 ft
	Long Section	200 ft
Taxiway Centerline Lighting[b]	Very Tight Curved Section	25 ft
	Tight Curved Section	50 ft
	Wide Curved Section	100 ft
	Straight Section	200 ft

[a]Special situations (e.g., very complex geometries) may require shorter spacing.
[b]Spacing should be halved when airfield is used under low-visibility conditions.

Evaluating lighting technology options for heliport lighting, Kimberlin et al. [3] discussed the potential use of light pipes to provide linear information that "may provide a clearer indication of location, glideslope, and outline than can be provided by the point source" and might also be more readily distinguished from background sources of light more likely to have a point-source appearance. More recently, Gallagher [4] investigated the potential for using light-emitting diode (LED) light source arrays in linear configurations to assist with delineation of airfield locations. Increased visual acquisition distances were found in operational field tests of such systems, but Gallagher [4] noted several potential shortcomings with the particular systems that were evaluated regarding their robustness for installation and the potential for sub-optimally installed systems to provide a non-continuous appearance. Parmalee [5] describes, in the context of pilot satisfaction, that linear elements can reinforce the orientation of a target, which can provide information that increases a pilot's confidence when approaching an airfield. An earlier study [6] of taxiway exit lighting design found that spacing centerline light fixtures more than 40 feet apart resulted in a non-continuous appearance.

In the context of roadway delineation, Kao [7] postulated that because intermittent roadway markings and delineation (i.e., dashed markings) contained gaps regarding the location of roadway edges, that such delineation was probably inferior to continuous markings, particularly under nighttime viewing conditions or during adverse weather. A few investigations of roadway delineation bear out Kao's [7] hypothesis. Steyvers and De Waard [8] measured driving speeds along rural roadways with various edge and centerline configurations and found differences in average driving speeds between roads with continuous and dashed edge line markings (higher speeds with continuous markings), but these differences were only found during daytime driving. In comparison, Van Driel et al. [9] reviewed several studies of roadway edge line characteristics and found no reliable differences on vehicle speeds overall between roads with continuous and with intermittent (dashed) edge lines. Zwahlen and Schnell [10] reported that visibility distances of centerlines consisting of continuous or dashed lines were longer for continuous lines.

The Oregon Department of Transportation evaluated two systems purporting to provide linear forms of roadway delineation. One was a lighted guidance tube, consisting of light-guiding film around a tubular shape illuminated by halogen lamps at each end [11]. These systems were mounted atop concrete Jersey barriers along a roadway curve edge. Not only did drivers navigating the curve report that they felt the tube system was helpful and increased their comfort level, driving speeds of vehicles entering the curve were sometimes reduced, thought to be caused by the increased visual information making drivers more aware of the extent and sharpness of the curve. Another system evaluated in Oregon was a retroreflective linear delineation system [12] mounted to the side edges of concrete barriers. These reflected light from vehicle headlamps at night to form a linear pattern along the outer edge of the curve. Speeds for vehicles entering and exiting the curves were lower than without the linear system installed. These studies demonstrate the complexity of understanding the purpose and impacts of visual delineation along roadways, because in some cases, more continuous delineation resulted in higher speeds, while in others it resulted in lower speeds. Nonetheless, it seems logical to assume that linear (in contrast to intermittent) delineation information could be beneficial in terms of providing more complete visual information to a pilot or driver.

METHODS

Experiment 1

In each of the first five experiments the primary display was a laptop computer screen, which served to display the experimental stimuli and record subjects' responses. Specifically, Experiment 1 was conducted to gauge the feasibility of using computer-generated images as the stimuli in the study. In Experiment 1, simulated views of taxiway intersections were developed having one of four geometric configurations: *Cross* – a 90^{o} intersection in which both intersecting taxiways continue beyond the intersection point; *Tee* – a 90^{o} intersection in which the taxiway from which the observer is viewing ends, with only perpendicular right and left turns possible at the intersection point; *Skew left* – a tee-like intersection in which the taxiway from which the observer is viewing ends, with a 30^{o} (non-sharp) left turn or a 150^{o} (sharp) right turn possible at the intersection point (traveling at high speeds, only a left turn would be possible); *Skew right* – a tee-like intersection in which the taxiway from which the observer is viewing ends, with a 150^{o} (sharp) left turn or a 30^{o} (non-sharp) right turn possible at the intersection point (traveling at high speeds, only a right turn would be possible).

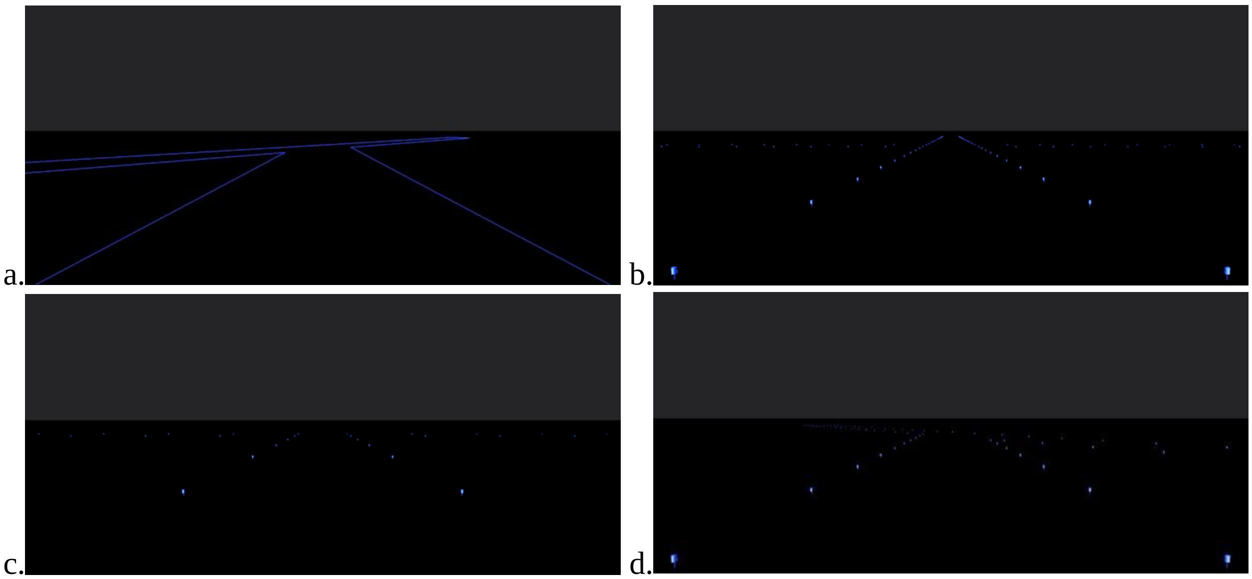


Figure 1. Examples of visual stimuli used in Experiment 1: a. continuous delineation on a skew right intersection; b. 50 ft spacing on a cross intersection; c. 100 ft spacing on a tee intersection; d. 50 ft spacing on a skew left intersection.

Taxiway edge delineation was provided by simulating elevated light fixtures spaced either 25, 50, 100 or 200 ft apart throughout all visible taxiways, or by using a continuous line to delineate all visible taxiway edges. Figure 1 shows examples of the visual stimulus conditions. All images in Experiment 1 consisted of blue delineation elements (having a luminance of about 7 cd/m^2) presented on a black background (luminance of 1 cd/m^2). A horizon line was made visible in the images using a dark gray background above the apparent horizon. The view simulated the appearance when seen 500 ft away from the intersection, at a height of 15 ft. No other elements were visible in each scene.

The experimental procedure was as follows: Subjects (8 subjects: 6 male/4 female, aged 24 to 66 years) viewed each of the twenty configurations (5 spacings: 0 [continuous], 25, 50, 100 and 200 ft, and 4 intersection types: cross, tee, skew left, skew right) in randomized order. The images were displayed using customized software that displayed each image for up to 10 s. Subjects were instructed to press any button on the computer keyboard once they could determine the type of intersection, and to do so as quickly as possible. As soon as they did so, the image was removed from the display and a legend linking each of the arrow keys on the computer keyboard to one of the intersection types was displayed. Subjects had as much time as needed to press the appropriate arrow key signifying the type of intersection they saw. The time between displaying each image and the initial key press was recorded, as well as the response given for the type of intersection. In this way, response times and accuracy could be measured.

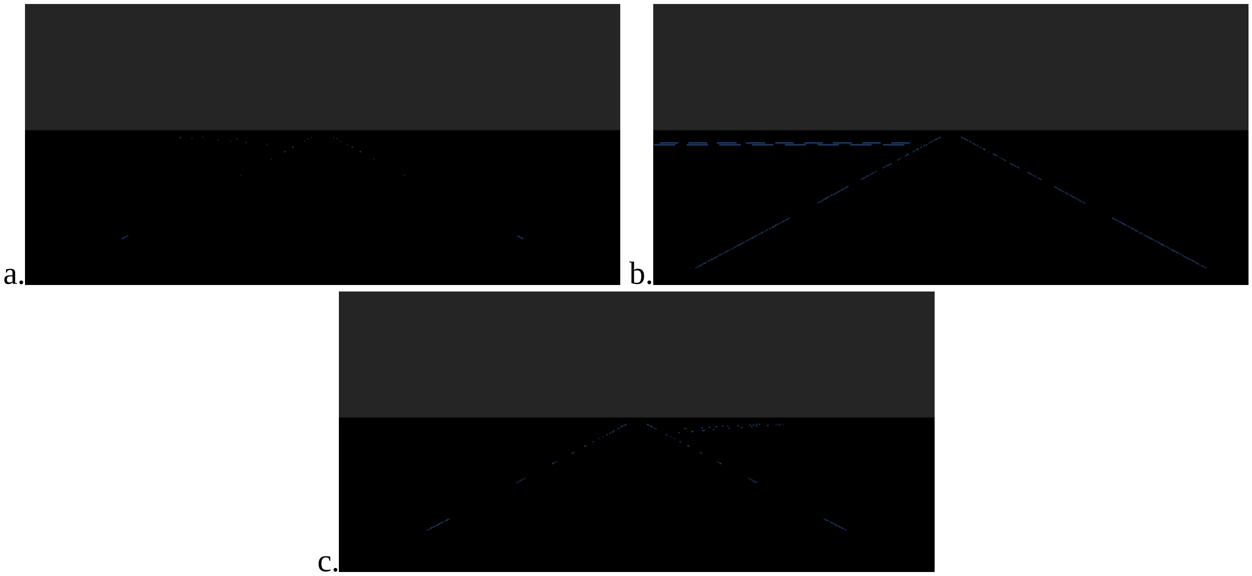


Figure 2. Examples of visual stimuli used in Experiment 2: a. 2-ft elements spaced 100 ft apart on a skew left intersection; b. 32-ft elements spaced 50 ft apart on a perpendicular left intersection; c. 8 ft elements spaced 50 ft apart on a skew right intersection.

Experiment 2

In Experiment 2, the same basic methodology of Experiment 1 was used, but the delineation conditions changed. The intersection types used in the images consisted of left or right turn-offs from a taxiway on which the observer would be traveling. The geometry of the turns could be either perpendicular (90^o) or skewed at an angle of 30^o to simulate a possible high-speed exit. Viewing distance and height remained the same as in Experiment 1. Linear elements (with a width of 4 inches) were used in all stimuli in which the length of the elements could be 2, 8 or 32 ft in length; the spacing (from leading edge to leading edge) could be 50, 100 or 200 ft. As in Experiment 1, no other elements other than the delineation was visible in each of the images. Ten subjects (7 male/3 female, aged 22 to 58 years) participated in Experiment 2. Figure 2 shows examples of the experimental stimuli used in this experiment.

Experiment 3

Experiment 3 used identical stimuli and procedures as Experiment 2, but they were presented against a visual field of background noise produced by randomly oriented and colored line segments distributed along the non-taxiway areas of the scene. Ten subjects (6 male/4 female, aged 22 to 56 years) participated in Experiment 3. Figure 3 illustrates examples of the visual stimuli used in this experiment.

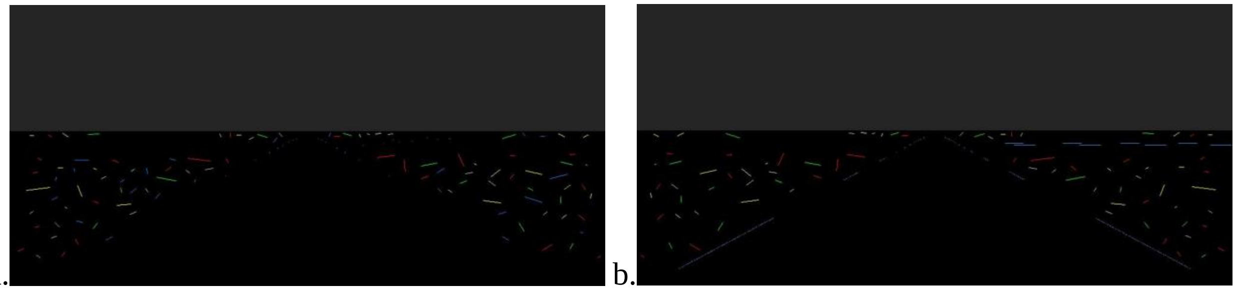
a.  b.

Figure 3. Examples of visual stimuli used in Experiment 3: a. 2-ft elements spaced 100 ft apart on a skew right intersection; b. 32-ft elements spaced 50 ft apart on a perpendicular right intersection.

Experiment 4

Each of the stimuli in Experiments 1 through 3 used edge lines to provide delineation, and these were always blue. As well, the images were static, displaying a non-moving scene. In order to assess the role of centerline linear characteristics (having different locations and colors than the elements displayed in Experiments 1 through 3) on visual perception, and to assess whether effects of element length and spacing differed under dynamic viewing conditions, Experiments 4 and 5 used animated simulations of the view while traversing down a runway toward an intersection with a taxiway, using colors representative of the lighting found on these facilities. The scenario that was created consisted of a view along a runway, containing white edge lights (4 in. by 4 in., and having a luminance of 120 cd/m²) spaced 200 ft apart on each side of the runway. Centerline lights along the runway were also 4 in. by 4 in. and spaced every 50 ft. The starting location for the animation was from a distance 2000 ft away from the taxiway intersection, with a viewing height of 10 ft and a simulated driving speed of 50 mph (73 ft/s). Within 500 ft of the intersection point between the runway and taxiway, the runway centerline lights changed to have a length of 2, 8 or 32 ft, and a spacing of 50, 100 or 200 ft.

The taxiway centerline lights had the same width, length and spacing characteristics as the runway centerline lights in a given scenario, but were green in color (luminance: 70 cd/m²). Taxiway edge lights were blue (luminance: 7 cd/m²), 4 in. by 4 in., and spaced 100 ft apart. The background of the lights was black (luminance: 1 cd/m²). The taxiway could be located on either the left or right side of the runway, and was angled at either a perpendicular (90^o) or skew (30^o) angle. Similar to previous experiments, subjects (9 subjects: 6 male/3 female, aged 24 to 52 years) were instructed to watch the animation on a laptop computer screen and, as soon as they could clearly identify the side and angular geometry of the taxiway intersections, were instructed to press a key on the laptop computer keyboard. The time taken to press the key was recorded. All conditions were presented in randomized order for each subject.

Experiment 5

Experiment 5 was conducted in an identical manner to Experiment 4, except a neutral density filter (transmission 25%) was placed over the computer screen. The result was to reduce the luminances of the background and colored elements in the scenes from those in Experiment 4 by a factor of four. The black background luminance was 0.25 cd/m², the luminance of the white runway edge and centerline lights was 30 cd/m², the luminance of the green taxiway centerline lights was 18 cd/m², and the luminance of the blue taxiway edge lights was 1.8 cd/m². The same subjects who participated in Experiment 4 also participated in Experiment 5.

Experiment 6

Following the laboratory studies a field experiment was conducted in a dark, enclosed building ("Watervliet Dome") formerly used as a skating rink and having a painted concrete floor. LED fixtures 8 ft long were constructed with blue and green LEDs in the bottom of a cut PVC pipe and covered with a diffuser. The LEDs were wired so that the central 2 ft, the central 4 ft, or all 8 ft of the light source could be switched on. In this experiment, only the green LEDs were used. Configurations with either 2 or 8 ft length, and either 25 or 100 ft spacing between fixtures were set up in random order, either simulating centerlines for a left or right, perpendicular or skew intersection. Subjects sat in an adjacent room with a window open to the space and after looking up from a laptop computer screen, were instructed to indicate the form of the simulated intersection as quickly as possible. Software on the laptop computers recorded and stored the response times.

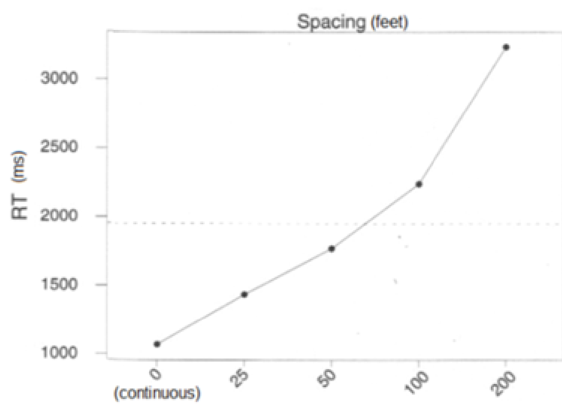


Figure 4. Mean response times for each of the delineation spacing conditions tested in Experiment 1.

RESULTS

Experiment 1

Figure 4 shows the response time results for Experiment 1 under each delineation condition, collapsed across all intersection types. A repeated-measured analysis of variance (ANOVA) revealed a statistically significant ($p<0.05$) effect of the delineation spacing condition on response times. Assuming the continuous delineation condition corresponds to a spacing of 0 feet, the response times increase monotonically as a function of spacing. The results of Experiment 1 suggested that the image display technique used in the present study was a feasible way to compare different delineation conditions. They also suggested that under the conditions used in Experiment 1, there were advantages to spacing edge lights closer than 200 ft apart, but less advantage under these conditions to spacing them 25 or 50 ft apart relative to 100 ft. However, even with a spacing of 25 ft, the edge delineator lights did not perform as well as the continuous linear delineation.

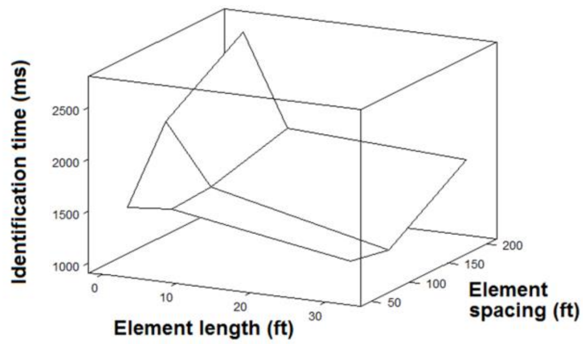


Figure 5. Mean response times as a function of length and spacing in Experiment 2.

Experiment 2

Since Experiment 1 used mainly discrete edge light delineation (except for completely continuous delineation), it was not clear if using delineation elements with distinct lengths rather than the discrete point sources of light would have any advantage, although there were differences found in Experiment 1 between completely continuous delineation and discrete lights spaced 25 ft apart. The conditions used in Experiment 2 were selected in order to begin to understand how these factors interact in terms of response times and accuracy. Figure 5 shows the mean response times plotted as a function of the length and the spacing of delineation elements. As might be expected, the longest response times occurred when the length was smallest (2 ft) and the spacing was greatest (200 ft), and the shortest response times occurred when the length was greatest (32 ft) and the spacing was smallest (50 ft). The response times (*RT*, in ms) could be predicted closely with a high goodness of fit (r^2=0.81) using a multiple linear regression model based on the logarithms of the length (*L*, in ft) and spacing (*S*, in ft):

$$RT = 286 - 607 \log L + 989 \log S \qquad \text{(Equation 1)}$$

In order to facilitate comparisons between the results of Experiments 1 and 2, the conditions of 50, 100 and 200 ft spacing using discrete delineators were compared to the same spacing conditions using the delineator length of 2 ft. This is because the images from Experiment 2 using 2 ft delineator lengths looked very similar in appearance to those from Experiment 1 using discrete delineation elements. There was a strong (r^2=0.90) correlation, and on average the corresponding response times differed only by about 13%. This correspondence suggests that the 2-ft-long delineator elements used in Experiment 2 may be effectively considered as point sources under the conditions underlying this study.

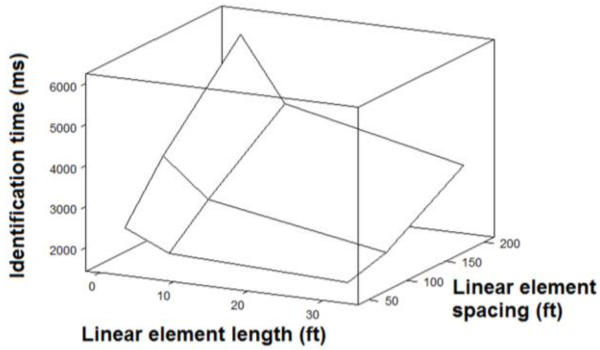


Figure 6. Mean response times as a function of length and spacing in Experiment 3.

Experiment 3

To assess whether and how the presence of visual noise might confound the relationships among identification, delineation element length and delineation element spacing, Experiment 3 was conducted using a high level of visual noise as illustrated in Figure 3. The surface plot in Figure 6 shows the mean response times plotted as a function of the delineation element length and the spacing of delineation elements. Figure 6 is very similar to Figure 5. The main difference between them is the scale of the vertical axes. A repeated-measures ANOVA revealed statistically significant ($p<0.05$) effects of spacing and length, and a statistically significant ($p<0.05$) interaction between these factors, on response times.

Indeed, when the response times for the corresponding conditions were compared between Experiments 2 and 3, there was a strong correlation ($r^2=0.86$) between them. The response times in Experiment 3 averaged about 1.8 times longer than for the corresponding conditions in Experiment 2. This suggests that the presence of visual noise does result in longer identification response times for delineation, but that the presence of visual noise, at least under the conditions in the present study, did not interact with either element length or spacing to influence response times.

Experiment 4

Experiment 4 differed from previous experiments in several important ways. Stimuli were presented dynamically through animations simulating the appearance of runway/taxiway delineation while traveling along a runway, and the stimuli were presented along centerlines rather than edge lines, while edge line conditions remained constant (and consisted of discrete point-source elements) for all stimuli. However, because the independent variables remained the same as in previous experiments, the results from Experiment 4 can be plotted in the same manner as those experiments. Figure 7 shows the mean response times in Experiment 4 as a function of element length and spacing. Again, the appearance of Figure 7 is very similar to Figure 5, but with very different values on the vertical axis. A repeated-measures ANOVA revealed statistically significant ($p<0.05$) effects of length and spacing, as well as a statistically significant ($p<0.05$) interaction between length and spacing, on mean response times.

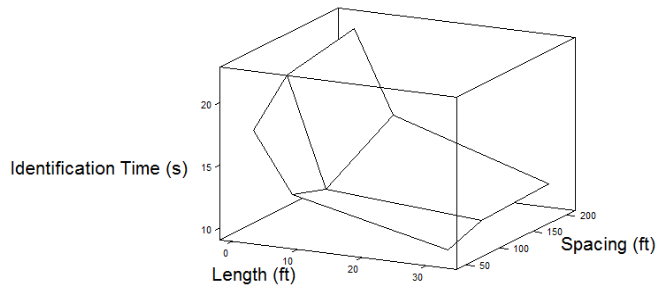


Figure 7. Mean response times as a function of length and spacing in Experiment 4.

There was a reasonably high correlation (r^2=0.73) between the results from Experiments 2 and 4, despite the large difference in the absolute response times (about 8.6 times longer for Experiment 4 than for Experiment 2). This finding suggests that the predictive model relating relative response times in Equation 1 can be applied to the conditions underlying Experiment 4, even though this experiment used dynamic animations and were based on centerline delineation characteristics.

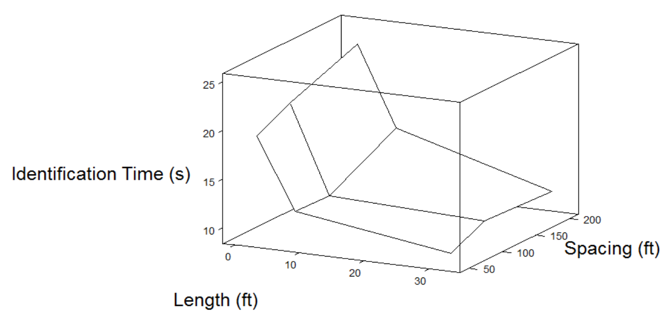


Figure 13. Mean response times as a function of length and spacing in Experiment 5.

Experiment 5

The conditions in Experiment 5 were identical to those in Experiment 4 except that the luminances of the animated displays were reduced by a factor of four. The mean response times in Experiment 5 are plotted in Figure 8 as a function of delineation element length and spacing. The visual appearance of Figure 8 is very similar to the figures displaying the results of the previous experiments. The correlation between the results of Experiments 2 and 5 for corresponding length and spacing was moderately high (r^2=0.69). Response times in Experiment 5 were about 8.8 times longer than in Experiment 2.

Experiment 6

Figure 9 shows the mean response times from Experiment 6 plotted in a similar manner as the data from previous experiments. There was a statistically significant (p<0.05) effect of spacing and a marginally significant (p=0.08) effect of length on response times, according to a repeated-measures ANOVA. For the combinations of length and spacing common to

Experiments 2 and 6, there was a moderately high (r^2=0.73) correlation between the mean response times in each experiment.

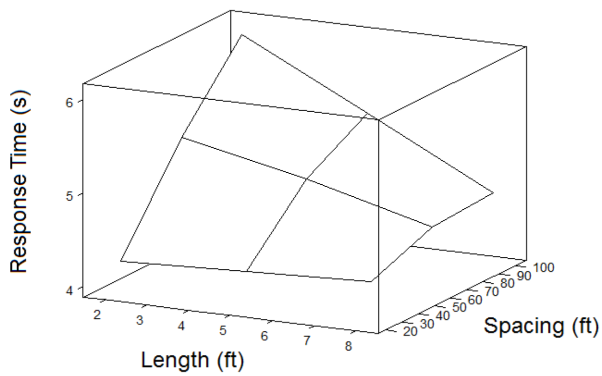


Figure 9. Mean response times as a function of length and spacing in Experiment 6.

DISCUSSION

Tradeoffs Between Length and Spacing

The results of the experiments described here are consistent in that they suggest there are tradeoffs between the length and spacing of delineation elements, whether they are used for centerline or edge line delineation. The specific response times depend upon the specific nature of the visual task, the presence of visual noise, and whether the observer is moving or stationary, but in each case the relative visual acquisition times were correlated with quantities derived from Equation 1. This suggests that Equation 1 can be used to assess the relative effectiveness of various combinations of delineation length and spacing compared to point-source delineation, assuming that the 2-ft length elements in Experiments 2 through 5 provided similar visual information as the point-source array elements in Experiment 1.

Table 2.
Combinations of Delineation Element Length and Spacing to Achieve the Same Relative Response Times Expected from 2-ft-long Delineation Elements Spaced at 50 and 100 ft.

Base Case 1	Element length	2 ft	**6.2 ft**	**12.0 ft**	**19.2 ft**
	Element spacing	50 ft	100 ft	150 ft	200 ft
	Relative response time	1784 ms	1784 ms	1784 ms	1784 ms
Base Case 2	Element length		2 ft	**3.9 ft**	**6.2 ft**
	Element spacing		100 ft	150 ft	200 ft
	Relative response time		2081 ms	2081 ms	2081 ms

As an example, Base Case 1 in Table 2 shows the predicted response time from Equation 1 for a combination of 2-ft (i.e., essentially point source) element lengths and 50-ft spacing. Assuming desired spacing values of 100, 150 or 200 ft, the minimum element length that gives the same relative response time is shown in the table. Base Case 2 in Table 2 also shows the same comparisons for 2-ft (i.e., essentially point source) element lengths spaced 100 ft apart. The minimum element lengths needed to produce the same relative response times are listed for spacing values of 150 and 200 ft. Thus, under the conditions of the present laboratory experiments, comparisons such as those in Table 2 can be used to identify combinations of delineation element length and spacing that would be expected to be equally visually effective as conventional centerline or edge line delineation using discrete point sources of light.

Caveats and Recommendations for Future Study

The present study used a limited range of background luminances (primarily, 1 cd/m² with limited use of 0.25 cd/m² as pavement luminances). In addition, the linear delineation elements used in the simulations for the present study were uniform in appearance. In comparison, the appearance of linear elements consisting of arrays of LED point sources such as those evaluated by Gallagher [4] could be highly non-uniform not only because of the optical systems used to distribute light, but also because of installation factors and inadvertent bending or warping of systems during or after installation. Field studies to measure pilot visibility and satisfaction with various linear delineation elements should be conducted to confirm whether the relationships between linear element length and spacing identified in the present experiments would hold under real-world conditions. In addition, measurements of runway and taxiway pavement luminance should be made in order to determine whether the contrast between the average luminance of pavement on an airfield and a linear element is related to its visual effectiveness.

Conclusions

Despite the inherent limitations of the present study, which used static and dynamic laboratory and field experiments rather than operational tests at real-world airports, the results from these experiments were robust and consistent in demonstrating relationships between the length and spacing of linear delineation elements. The data suggest that when properly defined, linear elements with sufficient length/spacing properties could provide shorter visual acquisition times than conventional point-source based delineation, or the spacing of linear elements could be increased relative to point-source spacing while maintaining visual effectiveness.

ACKNOWLEDGMENTS

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